4

PCT/EP 99 / 10497
09/869632
REC'D 25 FEB 2000
WIPO PCT
EP99/10497

PA 186318

# THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

December 15, 1999

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.

APPLICATION NUMBER: *09/223,885*
FILING DATE: *December 31, 1998*

**PRIORITY DOCUMENT**
SUBMITTED OR TRANSMITTED IN COMPLIANCE WITH RULE 17.1(a) OR (b)

By Authority of the
COMMISSIONER OF PATENTS AND TRADEMARKS

P. SWAIN
Certifying Officer

Attorney Docket No.: TH-1456 (US)
A Named Inventor/Application Identifier: C.A. Tjeenk Willink
Express Mail Label No.: EM006402909US
Title: EXTRACTION OF CONDENSABLES FROM GASES IN A WELLBORE
Date: December 31, 1998

A

12/31/98 jc612 U.S. PTO

JC560 U.S. PTO 09/223885 12/31/98

## UTILITY PATENT APPLICATION TRANSMITTAL UNDER 37 CFR 1.53(b)

Assistant Commissioner for Patents
Box Patent Applications
Washington, DC 20231

1. ☒ This application is a(n):
   - a. ☒ Original
   - b. ☐ Continuation-in-part of Application Serial No. ______filed ________
   - c. ☐ Divisional of Application Serial No. ________ filed ________
     ☐ Applicant(s) elect the invention of Group/Species ________
   - d. ☐ Continuation of Application Serial No. ______ filed ________

2. ☒ Specification
   - a. ☒ Pages 27
   - b. ☒ Drawing, Total sheets 7

3. ☐ Oath or Declaration
   - a. ☐ Newly executed (original or copy)
   - b. ☐ Copy from a prior application
     ☐ Please delete the following named inventors in the prior application: ____________________

4. ☐ Please amend the specification
   - a. ☐ By inserting before the first line:
     This is a ☐ continuation ☐ division ☐ continuation-in-part of Application Serial No. __________filed ________, the entire disclosure of which is hereby incorporated by reference
   - b. ☐ By inserting before the first line:
     This application claims the benefit of U.S. Provisional Application No. ___________, filed ______________, the entire disclosure of which is hereby incorporated by reference
   - c. ☐ Cancel claims _______

5. ☐ This application claims the benefit of Application Number _________ filed on _____________ in _________________ under 35 U.S.C. § 119, § 365(a), or § 365(b).
   (For originals)

6. ☐ Microfiche Computer Program (Appendix)

153(b)TRANS.DOC

7. ☐ Recognize as an associate attorney ______, Registration No. ________

8. ☒ Address all future communications to:
Del S. Christensen
Shell Oil Company
Legal – Intellectual Property
P. O. Box 2463
Houston, Texas 77252-2463

9. ☒ Fee Transmittal (duplicate enclosed)

| (1) FOR | (2) NUMBER FILED | (3) NUMBER EXTRA | (4) RATE | (5) CALCULATIONS |
|---|---|---|---|---|
| TOTAL CLAIMS (37 CFR 1.16(c)) | 25 - 20 = | 5 | X $ 18.00 = | $ 90.00 |
| INDEPENDENT CLAIMS (37 CFR 1.16(b)) | 4 - 3 = | 1 | X $78.00 = | 78.00 |
| MULTIPLE DEPENDENT CLAIMS (if applicable) (37 CFR 1.16(d)) | | | + $270.00 = | 0 |
| | | | BASIC FEE (37 CFR 1.16(a)) | $760.00 |
| | | | Total of above Calculations = | $928.00 |
| | | | TOTAL = | $928.00 |

10. ☒ Please charge Deposit Account No. 19-1800 in the amount of $928.00.

11. ☒ The Assistant Commissioner is authorized to charge all additional required fees or to credit overpayments, to Deposit Account No. 19-1800, including fees required under 37 CFR 1.17

12. ☒ Accompanying Application Parts

a. ☐ Recordal of Assignment and Assignment
b. ☐ Information Disclosure Statement/PTO-1449
c. ☐ Preliminary Amendment
d. ☒ A self-addressed, stamped return receipt postcard to be returned with the filing date and Serial No. thereon
e. ☐ Certified copy of priority documents

Respectfully submitted,

C. A. Tjeenk Willink

By [signature]
Hisr Attorney, Del S. Christensen
Registration No. 33,482
(713) 241-3997

P. O. Box 2463
Houston, Texas 77252-2463

153(b)TRANS.DOC

# EXTRACTION OF CONDENSABLES FROM GASES IN A WELLBORE

## FIELD OF THE INVENTION

The present invention relates to a method and apparatus for dehydrating or removing other condensable hydrocarbons from produced vapors within wellbores.

## BACKGROUND TO THE INVENTION

Downhole separators to remove water from gas as it is being produced are known, for example in US patent 5,444,684. This apparatus uses floating balls that float up and block a flowpath when a water level in the wellbore becomes high, and then as gas pressure builds, and forces the water level down, allowing production of gas that is free of liquid water. This apparatus is only capable of keeping liquid water out of produced gas. It is not capable of neither removing water from the wellbore, nor from lowering the dew point temperature of the produced gas.

US patent no. 5,794,697 also discloses a downhole separator for taking gas from a mixture of liquids and gas produced into a wellbore. This patent focuses on downhole compression of the gas and reinjection of the gas into a gas cap over the oil remaining in the formation. A separator is shown and described as an auger that imparts a swirling motion to the fluids, and then removal of the gas from the center of the swirl. This separator also does not lower the dew point temperature of the gas, but only separates existing phases.

It would be desirable to have a down-hole separator that not only removes liquid water, but that lowers the dew point temperature of the produced gas. This is because as gas flows up the wellbore, it may be cooled by heat transfer to the more shallow formations surrounding the wellbore, and by adiabatic expansion of the gas as it flows up the well. When the gas cools, water may then condense from the previously saturated gas stream.

Condensed liquids in a gas producing borehole could cause may problems. The separate liquid phase could considerably increase the static head within the wellbore, and therefore reduce the well head pressure and/or gas production. Depending on the flow regime that results, the liquids could build up until the bottom of the wellbore is expose to a considerable additional liquid head. Also, water could combine with hydrocarbons and/or hydrogen sulfide to form hydrates in the wellbore. These hydrates could plug the well. To prevent this, it is common to inject alcohols or gylcols into gas producing wellbores to prevent plugging with solid hydrates. This injection is relatively expensive, and further, results in more liquids being present in the wellbore. Spills of these liquids can be particular environmental concerns because they are by nature miscible with water.

Centrifugal force is useful for separation of liquids from streams of gases. Fluids, when rotating around a central axis will be accelerating toward the central axis, and inertia of the solids or liquids present will force the particles outward away from the central axis, against the flow of fluids. Fluids containing fewer liquids are then withdrawn from the center axis

of rotation, and liquids are removed from the outer surface of the separator. The rate of flow of particles outward is limited by the resistance of the fluid. This rate dictated by Stokes Law. Practically, only about five micron sized particles can be separated by conventional cyclonic separators.

European patent application No. EU496,128 discloses a method of removing a selected gaseous component from a stream of fluid containing a plurality of gaseous components, wherein the stream is induced to flow at a supersonic velocity through a conduit so as to decrease the temperature of the fluid in the conduit to below the condensation point of the selected component thereby forming condensed particles of the selected component. The conduit is provided with swirl imparting means to impart a swirling motion to the stream of fluid flowing at supersonic velocity. The condensed particles are extracted in a first outlet stream from a radially outer section of the stream and the remaining fluid is collected in a second outlet stream from a central part of the stream. The velocity in the radially outer section and in the central part of the stream is supersonic.

In an embodiment of the device for separating a gas from a gas mixture as disclosed in NL-8901841, separate shock waves occur in the first and second outlet streams, leading to a relatively large flow resistance of the fluid. Furthermore, the separation efficiency is relatively low so that substantial amounts of the condensed particles are still present in the second outlet stream. This reference does not suggest utilizing such an apparatus for separation of gases within a wellbore.

## SUMMARY OF THE INVENTION

In accordance with the invention there is provided a method and apparatus for removing condensables from a produced gas within a wellbore, the method comprising the steps of:

- inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which condensables will begin to condense forming a liquid droplets;
- inducing a swirling motion to the supersonic stream of fluid thereby causing the liquid droplets to flow to a radially outer section of a collecting zone in the stream;
- extracting the liquids into an outlet stream from the radially outer section of the collecting zone;
- collecting gases from which liquids have been removed and transporting the gases from which the liquids have been removed to a wellhead.

The apparatus is an apparatus effective for performance of this method.

The condensables removed are preferably water, and thus the present invention can prevent formation of hydrates and eliminate a need for injection of glycols or other components to prevent wellbore plugging by hydrates. The condensables removed could also be hydrocarbons, for example, propane and heavier hydrocarbons removed from methane and ethane.

In a preferred embodiment of the present invention, a shock wave caused by transition from supersonic to subsonic flow occurs upstream of the separation of the particles from the

collecting zone. It was found that the separation efficiency is significantly improved if collection of the particles in the collecting zone takes place after the shock wave, i.e. in subsonic flow rather than in supersonic flow. This is believed to be because the shock wave dissipates a substantial amount of kinetic energy of the stream and thereby strongly reduces the axial component of the fluid velocity while the tangential component (caused by the swirl imparting means) remains substantially unchanged. As a result the number density of the particles in the radially outer section of the collecting zone is significantly higher than elsewhere in the conduit where the flow is supersonic. It is believed that this effect is caused by the strongly reduced axial fluid velocity and thereby a reduced tendency of the particles to be entrained by a central "core" of the stream where the fluid flows at a higher axial velocity than nearer the wall of the conduit. Thus, in the subsonic flow regime the centrifugal forces acting on the condensed particles are not to a great extent counter-acted by the entraining action of the central "core" of the stream, so that the particles are allowed to agglomerate in the radially outer section of the collecting zone from which they are extracted.

Preferably the shock wave is created by inducing the stream of fluid to flow through a diffuser. A suitable diffuser is a supersonic diffuser. A diffuser may be, for example, a diverging volume, or a converging and then diverging volume.

In an advantageous embodiment, the collecting zone is located adjacent the outlet end of the diffuser.

The present invention may be practices in combination with other operations to effect drying of the fluid stream, or

practiced in front of conventional separators in order to reduce the size and or capacity required of the latter. Also, either of the stream containing liquids from the collecting zone or the stream from which the liquids have been separated could be subjected to an additional separation step, for example, a dryer or separator.

Advantageously, any gaseous fraction separated from the radially outer section of the collecting zone can be recycled back to the inlet, preferably using an inductor to increase the pressure back to the pressure of the inlet stream.

Another alternative in the practice of the present invention is to route liquids produced from the radial outer section of the collection zone and to a liquid-liquid separator, and remove a hydrocarbon phase from an aquous phase in the liquid-liquid separator. The liquid water phase could be, for example, reinjected into the formation and the liquid hydrocarbon phase produced either with the gases, or separately from the gases.

Suitably the means for inducing the stream to flow at supersonic velocity comprises a Laval-type inlet of the conduit, wherein the smallest cross-sectional flow area of the diffuser is preferably larger than the smallest cross-sectional flow area of the Laval-type inlet.

The present invention could also be utilized to reinject gas separated from condensables within a wellbore. For example, when multiple reservoirs are present (for example, stacked reservoirs) and it is desired to produce only condensates from the gas. Gases could be reinjected to prevent flaring or to maintain reservoir pressure. A separator of the present

invention could remove condensable fluids from gas, and the gas could then be reinjected from the same wellbore.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows schematically a longitudinal cross-section of a first embodiment of the separator useful in the practice of the present invention.

FIG. 2 shows schematically a longitudinal cross-section of a second embodiment of the device useful in the practice of the present invention.

FIG. 3 shows schematically a device according to the present invention within a wellbore.

FIG. 4 shows schematically an apparatus used to demonstate the device useful in the practice of the present invention.

FIG. 5 is a plot of particle size vs. equilibrium diameter for a selected set of conditions.

FIG. 6 is a schematic drawing of an embodiment of the present invention wherein the liquid stream from the separator of the present invention is routed to a liquid-liquid separator, and an aqueous phase is separated from a hydrocarbon phase, and the aqueous phase in reinjected into a formation from the wellbore.

FIG. 7 is a schematic drawing of an embodiment of the present invention wherein condensate is prouced, and gas is reinjected into a formation.

DESCRIPTION OF A PREFERRED EMBODIMENT

Copending US patent applications (Docket No. TH-1453 and TH-1454), both incorporated herein by reference, disclose various embodiments and variations of the present invention. In the disclosure of (TH-1454) a long expansion, leading to a relatively

slower decrease of temperature as a function of time (dT/dt- in the order of less than 100,000 °K/second) is taught in order to form larger drops of condensable fluids. The larger drops are then more readily separated from the vapor stream.

In Fig. 1 is shown a conduit in the form of an open-ended tubular housing 1. A fluid inlet 3 is provided at one end of the housing, a first outlet 5 for liquid laden fluid near the other end of the housing, and a second outlet 7 for substantially liquid-free fluid at the other end of the housing. The flow-direction in the device 1 is from the inlet 3 to the first and second outlets 5, 7. The inlet 3 is an acceleration section containing a Laval-type, having a longitudinal cross-section of converging - diverging shape in the flow direction so as to induce a supersonic flow velocity to a fluid stream which is to flow into the housing via said inlet 3. The housing 1 is further provided with a primary cylindrical part 9 and a diffuser 11 whereby the primary cylindrical part 9 is located between the inlet 3 and the diffuser 11. One or more (for example, four) delta-shaped wings 15 project radially inward from the inner surface of the primary cylindrical part 9, each wing 15 being arranged at a selected angle to the flow-direction in the housing so as to impart a swirling motion to fluid flowing at supersonic velocity through the primary cylindrical part 9 of the housing 1.

The wings are preferably provided with a very sharp leading edge, most preferably razor sharp. At high velocities, a blunt edge can cause shock waves in front of the wing. This shock wave can decrease the lift forces dramatically. Because the energy imparted to the swirling motion is directly proportional to the lift force of the wing, it is preferred that

this edge be sharp. The wing is also relatively flat, with a thickness preferably no more than about four millimeters at the base of the wing.

The diffuser 11 has a longitudinal section of converging - diverging shape in the flow direction, defining a diffuser inlet 17 and a diffuser outlet 19. The smallest cross-sectional flow area of the diffuser is larger than the smallest cross-sectional flow area of the Laval-type inlet 3.

The housing 1 further includes a secondary cylindrical part 17 having a larger flow area than the primary cylindrical part 9 and being arranged downstream the diffuser 11 in the form of a continuation of the diffuser 11. The secondary cylindrical part 17 is provided with longitudinal outlet slits 18 for liquid, which slits 18 are arranged at a suitable distance from the diffuser outlet 19.

An outlet chamber 21 encloses the secondary cylindrical part 17, and is provided with the aforementioned first outlet 5 for a stream of concentrated liquids.

The secondary cylindrical part 17 debouches into the aforementioned second outlet 7 for substantially gas.

Normal operation of the device 1 is now explained.

A stream containing micron-sized particles is introduced into the Laval-type inlet 3. As the stream flows through the inlet 3, the stream is accelerated to supersonic velocity. As a result of the strongly increasing velocity of the stream, the temperature of the stream may decrease to below the condensation point of heavier gaseous components of the stream (for example, water vapors) which thereby condense to form a plurality of liquid particles. As the stream flows along the delta-shaped

wings 15 a swirling motion is imparted to the stream (schematically indicated by spiral 22) so that the liquid particles become subjected to radially outward centrifugal forces. When the stream enters the diffuser 11 a shock wave is created near the downstream outlet 19 of the diffuser 11. The shock wave dissipates a substantial amount of kinetic energy of the stream, whereby mainly the axial component of the fluid velocity is decreased. As a result of the strongly decreased axial component of the fluid velocity, the central part of the stream (or "core") flows at a reduced axial velocity. This results in a reduced tendency of the solids and condensed particles to be entrained by the central part of the stream flowing in the secondary cylindrical part 17. The condensed particles can therefore agglomerate in a radially outer section of a collecting zone of the stream in the secondary cylindrical part 17. The agglomerated particles form a layer of liquid which is extracted from the collecting zone via the outlet slits 18, the outlet chamber 21, and the first outlet 5 for substantially liquid.

The stream from which condensable vapors have been removed is discharged through the second outlet 7 for substantially liquid-free gas.

In Fig. 2 is shown a second embodiment of the device for carrying out the invention. This device has an open-ended tubular housing 23 with a Laval-type fluid inlet 25 at one end and a first outlet 27 for stream containing the solids and any condensed liquid at the other end of the housing. The flow-direction for fluid in the device is indicated by arrow 30. The housing has, from the inlet 25 to the liquid outlet 27, a primary

substantially cylindrical part 33, a diverging diffuser 35, a secondary cylindrical part 37 and a diverging part 39. A delta-shaped wing 41 projects radially inward in the primary cylindrical part 33, the wing 37 being arranged at a selected angle to the flow-direction in the housing so as to impart a swirling motion to fluid flowing at supersonic velocity through the housing 23. A tube-shaped second outlet 43 for substantially gas extends through the first outlet 27 coaxially into the housing, and has an inlet opening 45 at the downstream end of the secondary cylindrical part 37. The outlet 43 is internally provided with a straightened (not shown), e.g. a vane-type straightener, for transferring swirling flow of the gas into straight flow.

The delta-shaped wing is preferably a triangular profile shape, with a leading edge that is sloped to a wing tip so that the leading edge is "subsonic", meaning that a "mach" line extending from the base of the wing is at greater angle from the cord of the wing at the base than the leading edge of the wing. The trailing edge is preferably also subsonic. The wing preferably extends across the vortex tube or conduit for about two thirds of the diameter.

Normal operation of the second embodiment is substantially similar to normal operation of the first embodiment. Supersonic swirling flow occurs in the primary cylindrical part 33 and a shock wave occurs near the transition of the diffuser 35 to the secondary cylindrical part 37. Subsonic flow occurs in the secondary cylindrical part 37. The stream containing the solid particles and any condensed liquids is discharged through the first outlet 27, and the dried gas is

discharged through the second outlet 43 in which the swirling flow of the gas is transferred into straight flow by the straightener.

In the above detailed description, the housing, the primary cylindrical part, the diffuser and the secondary cylindrical part have a circular cross-section. However, any other suitable cross-section of each one of these items can be selected. Also, the primary and secondary parts can alternatively have a shape other than cylindrical, for example a frusto-conical shape. Furthermore, the diffuser can have any other suitable shape, for example without a converging part (as shown in Fig. 2) especially for applications at lower supersonic fluid velocities.

Instead of each wing being arranged at a fixed angle relative to the axial direction of the housing, the wing can be arranged at a changing angle with respect to the direction of flow, preferably in combination with a spiraling shape of the wing. A similar result can be obtained by arranging flat wings along a path of increasing angle with respect to the axis of initial flow.

Furthermore, each wing can be provided with a raised wing-tip (also referred to as a winglet).

Instead of the diffuser having a diverging shape (Fig. 2), the diffuser alternatively has a diverging section followed by a converging section when seen in the flow direction. An advantage of such diverging - converging shaped diffuser is that less fluid temperature increase occurs in the diffuser.

Referring now to FIG. 3, an apparatus of the present invention is shown in a wellbore. A formation from which hydrocarbons are being produced 301 is below an overburden 302,

and is penetrated by a wellbore 303. The wellbore provides communication from the formation through perforations 305 which are shown as packed with sand 306 to prevent collapse of the formation into the perforations. A casing 307 is placed in the wellbore and secured with cement 308 that is placed by circulation from the inside of the casing and out the outside to provide support. The cement is followed by a cement plug 309 that remains in the bottom of the casing, and is caught by a lip 310 provided in the bottom segment of casing for that purpose.

Gas flowing from the formation is forced through the separator of the present invention by a sealing packer 311 that is effective to isolate the wellbore in the region of the producing formation. Gas from the producing formation goes through the inlet Lavel nozzle 312 where supersonic velocities are created, and wing 313 induces a swirl to the supersonic flow. A sufficiently long flow path 314 is provided for the supersonic flow region so that a temperature drop as a function of time is less than about 100,000 °C/second. A sufficiently low rate of temperature decrease results in larger, easier to separate droplets. A diffuser section 315 is provided to create a sonic shock wave, preferably just upstream of the separation of the liquids from the radially outer section from the vapors, which are captured in a vortex finder 316 and routed to the surface through a production tubing 317. Flow from the radially outer section of portion of the collection section 318 is shown as being routed to the outside of the production tubing to an annular volume between the casing 307 and the production tubing 317 by way of a tangential outlet 319. The tangential outlet can help separate liquids from the vapors in the liquid stream.

Although the stream being removed from the radially outer section of the collection section is initially liquid, considerable vaporization may occurs as the gas is recompressed in the shock wave induced by the diffuser. But the liquid could be sufficiently concentrated that even this rise in temperature does not vaporize all of the condensables in the stream. A typical sucker-rod pump or downhole electrical pump 320 is shown to remove liquid water that has fallen back to the isolation packer 311. Reinjection into the formation is also possible, both for liquids and gases, possibly with the help of electric submersible pumps.

The stream concentrated in water and/or condensate is preferably of such a composition that addition of components to prevent formation of hydrates is not needed. Even if hydrate inhibition is desirable, the amount of hydrate inhibition compound needed will be considerably reduced because of the need to treat only the smaller volume of fluid to be treated.

Referring now to FIG. 6, an embodiment of the present invention is shown wherein a seperator of the present invention 601 is within a wellbore 602 that is perforated in a hydrocarbon gas producing formation 603. The wellbore is shown as cased with a caseing 604 that is cemented with cement 605, with a cement shoe 606. A packer 607 isolates the producing portion of the wellbore, forcing the produced gas into an inlet 608 to the separator of the present invention. A wing 609 induces a swirl to the supersonic gases that have passed through the Laval nozzel 610, and condensed water and hydrocarbons are collected and exit the separator from a liquid outlet 611. Liquids from the liquid outlet pass to a liquid-liquid separator 612. The liquid-liquid

separator can be any kind known in the art. The liquids are separated into a hydrocarbon phase, which is routed to a wellhead 613 at the surface 614, through a tubing 618 such as a coiled tubing. An aqueous phase 615 which is routed through perforations 616 to a formation. A second set of packers 619 is shown as isolating a section of the wellbore for reinjection of the aqueous phase. Vapor from which the condensables including water have been removed are routed through a production tubing 617 to the wellhead where produced gas 620 and produced hydrocarbon liquids 621 are gathered separately.

Referring now to FIG. 7, a wellbore 701 is shown with a casing 714 perforated by perforations 702. Cement 703 secures the casing in a formation 704 from which hydrocarbons are produced, the cement having been forced down the casing by pressure behind a cement shoe 715. The hydrocarbons are forced through a separator 705 of the present invention. The separator of the present invention has a liqiuid outlet 706 and a vapor outlet 707. The liquid outlet is in communication with a production tubing 708. The vapor outlet is in communication with a segment of the volume inside the casing 709 that is in communication with a second formation 710 to which the vapors are to be reinjected through more perforations 711. The segement of the volume inside of the casing in communication with the second formation is isolated by and upper packer 712 and a lower packer 713.

To increase the size of the condensed particles, the boundary layer in the supersonic part of the stream can be thickened by, for example, injecting a gas into the supersonic part of the stream. The gas can be injected, for example, into

the primary cylindrical part of the housing via one or more openings provided in the wall of the housing. Suitably part of the gas from the first outlet is used for this purpose. The effect of such gas-injection is that less condensed particles form in the supersonic part of the stream resulting in larger particles and better agglomeration of the larger particles.

The swirl imparting means can be arranged at the inlet part of the conduit, instead of downstream the inlet part.

EXAMPLE

A test apparatus for the present invention was prepared, and demonstrated for separating water vapor from air at ambient conditions. Fig. 4 is referred to for the general configuration of the apparatus used.

In this example the air 425 is pressurized to 1.4 bar(abs.) by means of a blower 401 to provide pressurized air 426. After the blower the air is cooled to about 25 to 30 $^{0}$C by fin cooler 402, located in a vessel 418, and water 419 is sprayed into the vapor space below the cooler 420 to ensure that the air is near water saturation (RV = 90%). This water saturated air 427 is fed to the feed liquid-vapor separator 403 where the water is separated with a small amount of slip air into a wet stream 421, coming along with this water liquid stream and dried air 422.

In this example, the apparatus is provided with tubular flow ducts although the same results can be achieved for rectangular or asymmetric duct cross sections. Therefore diameters of devices are mentioned and always refer to the inner diameter.

The typical inlet conditions are summarized below:

1. Mass flow rate : 1.2 kg/s
2. Inlet pressure : 1400 mbar(abs)

3. Inlet temperature : 25 °C

4. Inlet humidity : 90 %

The device condenses water vapor, resulting in a mist flow containing large number of water droplet, typically $10^{13}/m^3$. Therefore the final temperature (T) and pressure (P) at the outlet of the Lavel nozzle and through the supersonic region have to be determined such that the water vapor fraction becomes negligible small. In this case it will be T = -28 °C and P = 680 mbar(abs.) in the supersonic zone 428.

The nozzle throat cross-section is sized in order to obtain the required flow rate. Considering the inlet conditions required to result in sufficient separation of condensable, this throat diameter 404 is 70 mm. The inlet diameter 405 is 300 mm, although its value is not significant with respect to the working of the apparatus. The nozzle outlet diameter 400 is 80 mm in order to obtain supersonic flow conditions; typically the corresponding Mach number, M = 1.15.

The lengths of the nozzle are determined by the cooling speed, which for this case is 19000 K/s. Persons of ordinary skill in the art can determine pressure and temperature profiles for the flow through the apparatus, and thus the cooling rate. The cooling speed determines the droplet size distribution. Lowering the value of the cooling speed results in larger average droplet sizes. The lengths of the nozzle are:

L1, 406 : 700 mm : from nozzle inlet to nozzle throat

L2, 407 : 800 mm : from nozzle throat to nozzle outlet

In order to decrease frictional losses the wall roughness is small, preferably 1 micron or less.

Depending on the application any rigid material can be used for the nozzle device, as long as the before mentioned design parameters are respected.

The vortex tube 408 is connected between the nozzle outlet and the diffuser. In the vortex tube a wing-like, swirl imparting internal 409 is present. At the edge of this internal a vortex is created on the upper (low-pressure) side and shed from the plane, preferably at the trailing edge. The root cord of this wing-like plate is attached to the inner wall of the vortex tube.

The sizing of the vortex tube is related to the nozzle outlet diameter, which is the inlet diameter of the vortex tube 400 is 80 mm. In this case vortex tube is slightly conical; the diameter is increasing linear to 84 mm (423) over a length of approximately the cord length of the wing.

After the conical section of the vortex tube 410, the vortex tube diameter is constantly 84 mm over a length were the droplets will be depositing on the inner wall (separation length). These two lengths are:

L3, 410 : 300 mm : from wing apex to wing trailing edge

L4, 412 : 300 mm : from wing trailing edge to diffuser

The sizing of the wing internal depends on the preferred circulation or integral vorticity. This circulation is typical 16 $m^2/s$ resulting from a wing cord length of 300 mm, a wing span at the trailing edge is 60 mm and at an incidence of the wing cord at the axis of the tube of $8^o$. The sweepback angle of the leading edge (from perpendicular to the flow) is $87^o$ and the sweepback angle of the trailing edge is $40^o$. The edges of the wing are sharp. The plane of the wing is flat and its profile is

extremely slender. The thickness of the wing is about 4 mm at the root. The wing is at an 8° angle to the axis of the tube.

In the drainage section withdrawal of liquids out of the vortex tube is achieved. The drainage section is not a sharp distinguished device but is an integral part of the vortex tube, by means of, for example, slits, porous materials, holes in the vortex tube walls; or, as shown in FIG. 4, is an integral part of the diffuser by means of a vortex finder 413 (co-axial duct). In this example, a vortex finder (co-axial duct) is placed centrally in the duct after the shock wave, which is present directly after the vortex tube in the first diffuser part 414.

The sizing of the vortex tube is dependent on the diameter ratio between diffuser diameter at that location 424(90 mm at the inlet) and vortex finder inlet diameter at that point 425(85 mm at the inlet). The cross-sectional area difference between the latter two determines the minimal flow, which is extracted from the main stream containing the liquids. In this case this minimal flow is 10% of the main flow i.e. 0.12 kg/s. The diffuser length 433 is 1500 mm.

In the diffuser the remaining kinetic energy in the flow is transformed to potential energy (increase of static pressure). It is desirable to avoid boundary layer separation, which can cause stall resulting in a low efficiency. Therefore the half divergence angle of the diffuser should be preferably less then $5^0$ as in this case $4^0$ is used. The diffuser inlet diameter is the same as the vortex finder inlet diameter (85 mm). The outlet diameter 415 of the diffuser is 300 mm, and the dry air at this point is at about atmospheric pressure. The performance of this apparatus was measured by two humidity sensors (capacitive

principle: manufacturer 'Vaisala') one at the air inlet 416 and the other at the dried air outlet 417, both were corrected for temperature and pressure. The typical values of the inlet water fractions were 18-20 gram of water vapor per kg dry air. Typical values of the outlet water were 13-15 gram of water vapor per kg dry air. This can be expressed in separation efficiencies of about 25% of the water vapor in the inlet removed. This also corresponds to the separation of liquids condensed in the super sonic region, because most of the liquid water present in the inlet stream condenses at that point.

Separation in the apparatus of the present invention is due to inertia forces of a dispersed liquid phase transported in a gaseous fluid. A swirling motion of the fluid (vortex flow) imparts inertia forces in which the heavier constituent's i.e. liquid particles, drifting in outer radial direction with respect to the gas streamlines.

Particle drift in gravitational or centrifugal fields is described by Stokes relationships, solving the momentum equations. In a vortex two counteracting phenomena - with respect to the forces acting on said particle - taking place known as: Vortex strength ($\Gamma$) and Sink strength ($Q$). The vortex strength ($\Gamma$) forces the particle to flow in tangential direction causing a centrifugal force acting on this particle so a positive radial drift of the particle results. The sink strength ($Q$) causes a radial inflow of gas to the vortex axis, resulting in a negative radial drift of the particle. For every vortex there exists a radial position for a particle in the vortex where the resulting force acting on the particle is zero. On this particular radial position - known as the equilibrium radius

($R_{eq}$) - the particle has no motion in radial direction anymore. When $R_{eq}$ exceeds the conduit radius ($R_{conduit}$) the droplet is deposited on the wall, which enables separation of liquids. From Stokes law it is known that:

$$R_{eq} = \frac{\Gamma}{\sqrt{Q}} \cdot \sqrt{2\pi . \tfrac{2}{9} . \frac{d^2}{4\pi^2 . \nu} \left( \frac{\rho_L}{\rho_G} - 1 \right)}$$

and:

$$Q = 2\pi r V_{rad.}$$

$$\Gamma = 2\pi r V_{tan.}$$

wherein: $r$ is the radius from the center of the vortex;

$V_{rad.}$ is the velocity radially toward the axis of rotation of the vortex; and

$V_{tan.}$ is the tangential velocity of the fluid.

Separation is achieved when: $R_{eq} \geq R_{conduit}$.

The sink strength Q is typically between about 1 and about 5 percent of the circulation in vortexes utilized in the present invention. Therefore:

$$Q = 2\pi r V_{rad.} \approx (0.01)\Gamma = (0.01) 2\pi r V_{tan.}$$

Fig. 5 shows the minimal $R_{conduit}$ as function of the particle diameter (d) for conditions of:

| | | | |
|---|---|---|---|
| Circulation | : $\Gamma$ = | 48.3 | $m^2/s$ |
| Sink strength | : $Q$ = | 0.5 | $m^2/s$ |
| Kinematic viscosity | : $\nu$ = | $1.5 . 10^{-5}$ | $m^2/s$ |
| Gas density | : $\rho_G$ = | 0.3 | $kg/m^3$ |
| Particle density | : $\rho_L$ = | 1000 | $kg/m^3$ |

This figure shows that for a particle diameter of 1 um the maximum allowable conduit radius should be equal to or less then 200 mm in order to get separation ($R_{eq} \geq R_{conduit}$).

We claim:

1. A method for removing condensables from gases being produced from a wellbore, the wellbore extending from a wellhead to a gas producing formation, the method comprising the steps of:

inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which condensables will begin to condense forming a liquid droplets;

inducing a swirling motion to the supersonic stream of fluid thereby causing the liquid droplets to flow to a radially outer section of a collecting zone in the stream;

extracting the liquids into an outlet stream from the radially outer section of the collecting zone; and

collecting gases from which liquids have been removed and transporting the gases from which the liquids have been removed to a wellhead.

2. The method of claim 1 further comprising the step of: creating a shock wave in the stream so as to decrease the axial velocity of the fluid to subsonic velocity wherein extraction water into an outlet stream from the radially outer section of the collecting zone is upstream of the shock wave and downstream the location where the swirling motion is imparted.

3. The method of claim 1 wherein the shock wave is created by inducing the stream of fluid to flow through a diffuser.

4. The method of claim 1 wherein transporting the gases from which the water has been removed to a wellhead is accomplished through a production tubing, and the condensables are transported to the surface as a through a different flowpath.

5. The method of claim 1 wherein the condensables are transported to the surface by being pumped with a pump selected from the group consisting of a sucker rod pump and an electrical submersible pump.

6. The method of claim 1 wherein water removed from the gas as a condensable component.

7. A method to dehydrate gas produced from a formation comprising:

removing, in a wellbore, at least a portion of water vapor produced with a produced gas stream; and

transportation of the dehydrated gas to the surface.

8. The method of claim 7 wherein the gas is dehydrated by accelerating the gas to supersonic velocities, thereby causing cooling of the gas to a temperature below a temperature at which water condenses from the gas, and separating liquid water from the cooled gas stream.

9. A wellbore for producing gas from a subterranean formation, the wellbore comprising:

an acceleration section wherein gas from the subterranean formation is accelerated to a supersonic velocity;

a swirl imparting section that imparts a swirling motion to the gas;

a collection zone from which a gas stream containing reduced amount of condensables is removed; and

a radially outer section of the collecting zone with a radially outer section from which condensables can be collected.

10. The wellbore of claim 9 further comprising a shock wave initiator downstream of the swirl imparting section.

11. The wellbore of claim 10 wherein the shock wave initiator is a diffuser.

12. The wellbore of claim 10 wherein the shock wave initiator is located so that the shock wave is upstream the collecting zone.

13. The wellbore of claim 10, wherein the shock wave is induced by a diffuser.

14. The wellbore of claim 13, wherein the acceleration section comprises a Laval-type inlet of the conduit, and wherein the smallest cross-sectional flow area of the diffuser is larger than the smallest cross-sectional flow area of the Laval-type inlet.

15. The wellbore of claim 9 wherein said collecting zone is located adjacent the outlet end of the diffuser.

16. The wellbore of claim 9 wherein the gas containing reduced amount of condensables is collected in a vortex catcher.

17. The wellbore of claim 9 wherein the swirl imparting section that imparts a swirling motion to the stream comprises a wing device.

18. The wellbore of claim 17 wherein the wing is a triangular shape wing at an angle to the axial flow of supersonic fluids of between about 4 and 12 degrees.

19. The wellbore of claim 18 wherein the leading edge of the wing is at an angle to the axial flow that results in a subsonic leading edge.

20. The wellbore of claim 19 wherein the trailing edge of the wing is at an angle to the axial flow that results in a subsonic trailing edge.

21. The wellbore of claim 20 wherein the wing has an changing angle with respect to the direction of axial flow between the leading edge and the trailing edge.

22. The wellbore of claim 18 wherein the wing includes an end piece that is at about a 90 degree angle to the surface of the wing.

23. The wellbore of claim 9 further comprising a liquid-liquid separator to which collected condensables are routed, the liquid-liquid separator capable of separating the condensables into an aqueous and a hydrocarbon phase.

24. The wellbore of claim 23 further comprising tubing for production of liqiud hydrocarbons to the surface, and a means for reinjecting the aqueous phase into a formation.

25. A method for removing condensables from gases being produced from a wellbore for production of the condensables, the wellbore extending from a wellhead to a gas producing formation, the method comprising the steps of:

inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which condensables will begin to condense forming a liquid droplets;

inducing a swirling motion to the supersonic stream of fluid thereby causing the liquid droplets to flow to a radially outer section of a collecting zone in the stream;

extracting the liquids into an outlet stream from the radially outer section of the collecting zone; and

collecting gases from which liquids have been removed and reinjecting the gases from which the liquids have been removed into the gas producing formation.

TH 1456

## A B S T R A C T

EXTRACTION OF CONDENSABLES FROM GASES IN A WELLBORE

A method and apparatus are provided for removing condensables such as water from gases being produced from a wellbore, the wellbore extending from a wellhead to a gas producing formation, the method including the steps of: inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which components will begin to condense; inducing a swirling motion to the supersonic stream of fluid thereby causing the condensed components to flow to a radially outer section of a collecting zone in the stream; extracting the condensed components into an outlet stream from the radially outer section of the collecting zone; and transporting the gases from which the condensables have been removed to a wellhead. The apparatus is an apparatus effective for performance of this method. In another aspect the present invention is a method to produce gases wherein water is removed from the gases within the wellbore resulting in a gas that is above the dewpoint temperature of the gas being transported up the wellbore. Another embodiment of the present invention includes reinjection of gas back into the gas producing formation and production of the separated liquids.

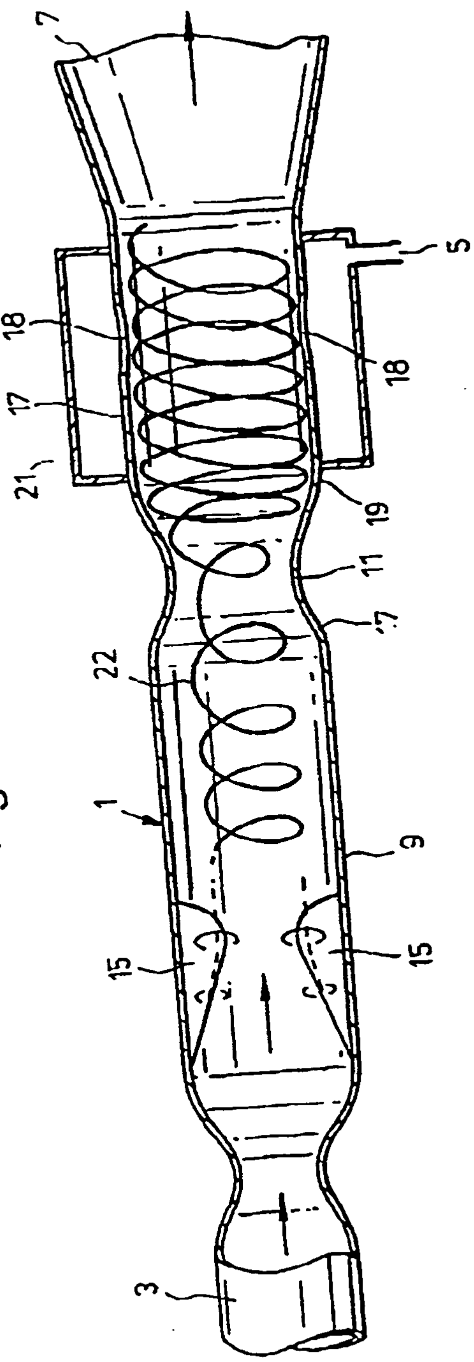
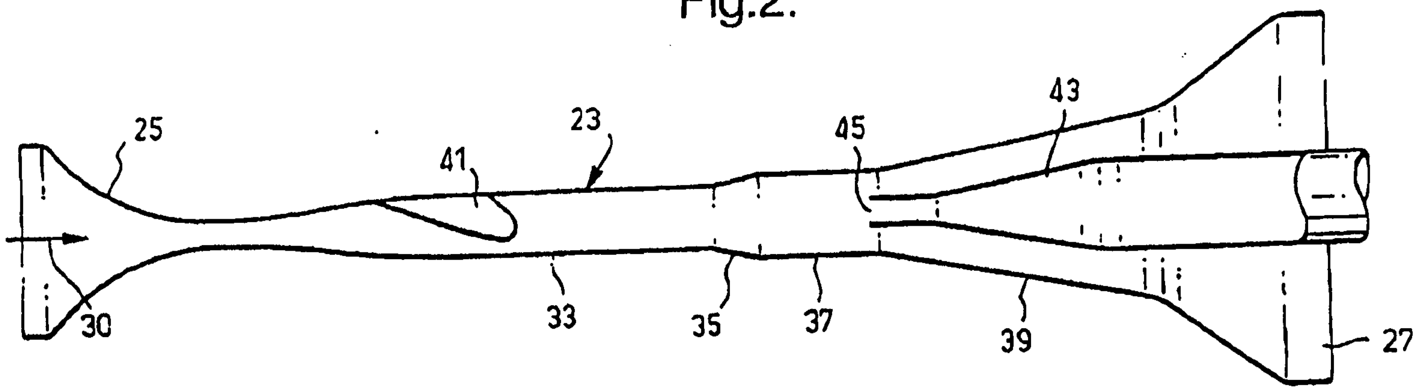



Fig.1

TH-1456

Fig.2.



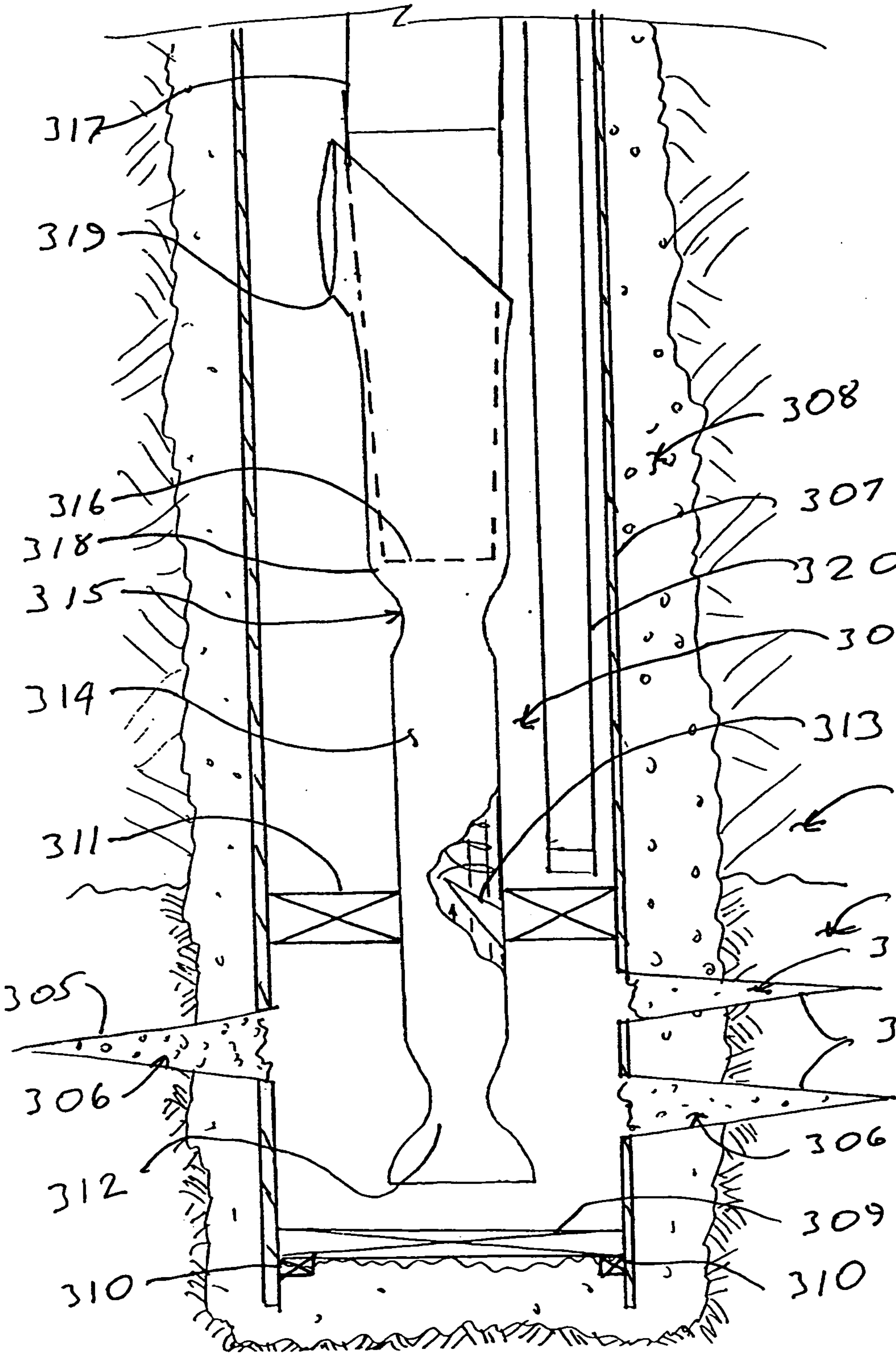

317
319
308
316
307
318
320
315
303
314
313
302
311
301
306
305
305
306
306
312
309
310
310

FIG.3

TH-1456

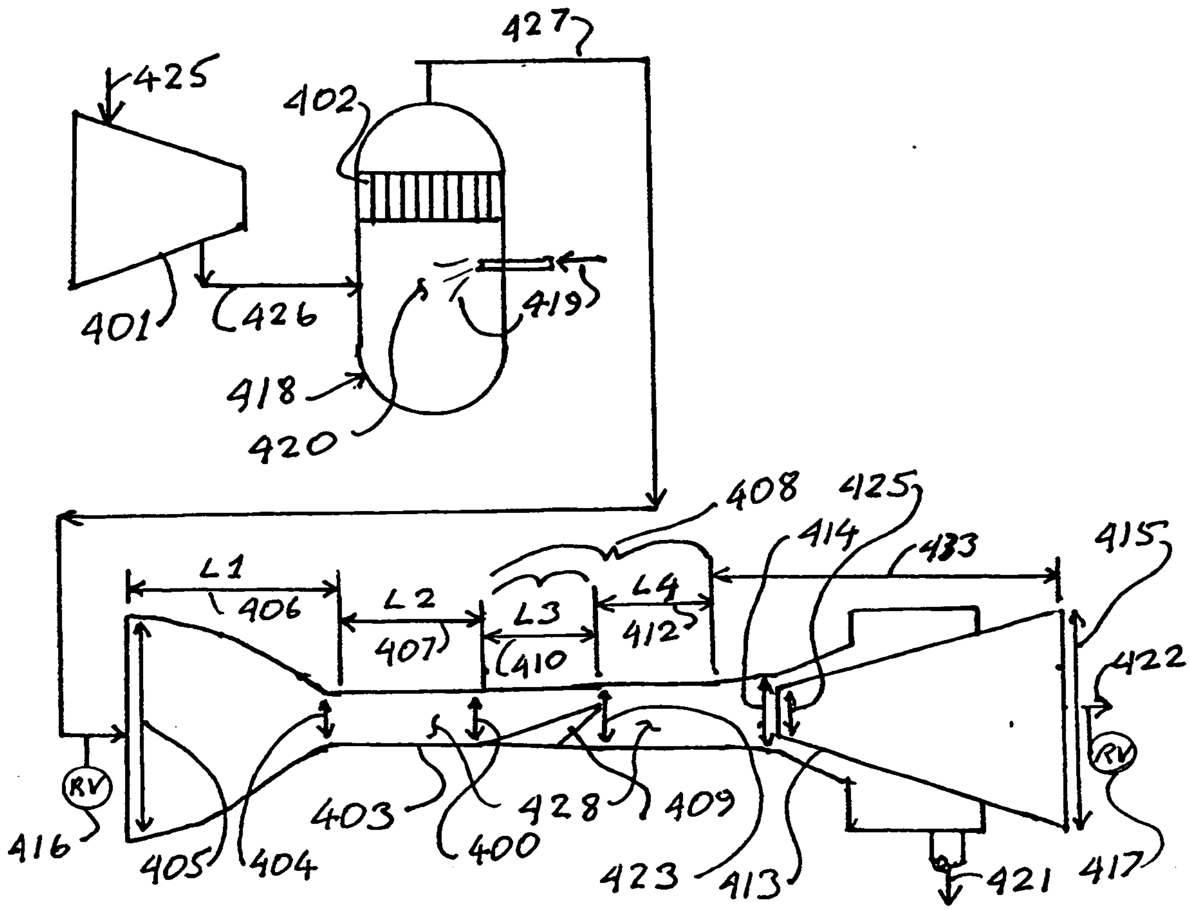

427
425
402
401
426
419
418
420
408
425
414
433
415
L1
406
L2
407
L3
410
L4
412
422
RV
416
405
404
403
400
428
409
423
413
421
RV
417

FIG. 4

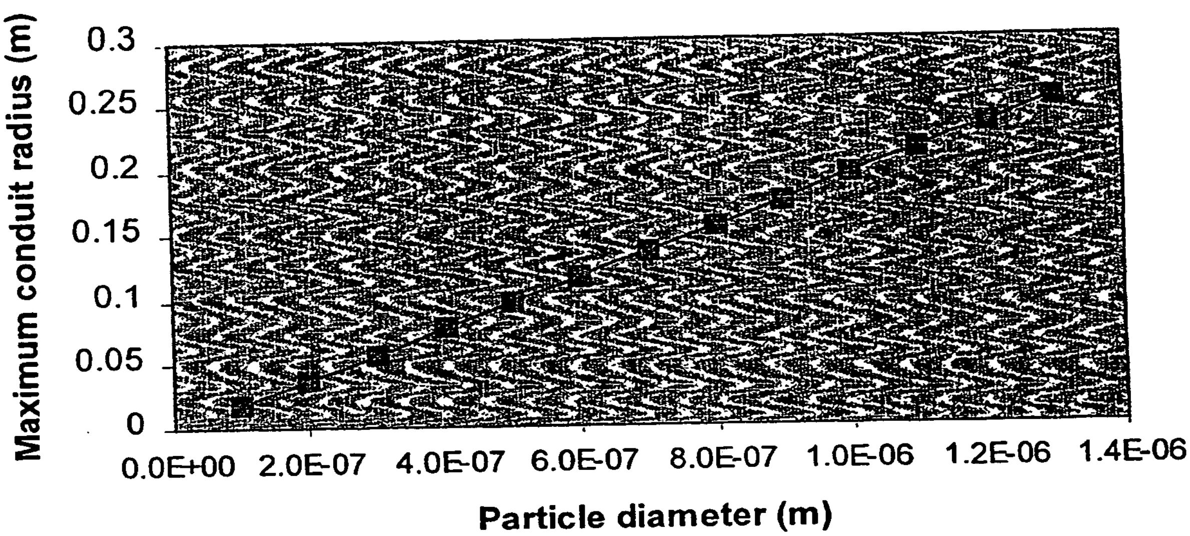
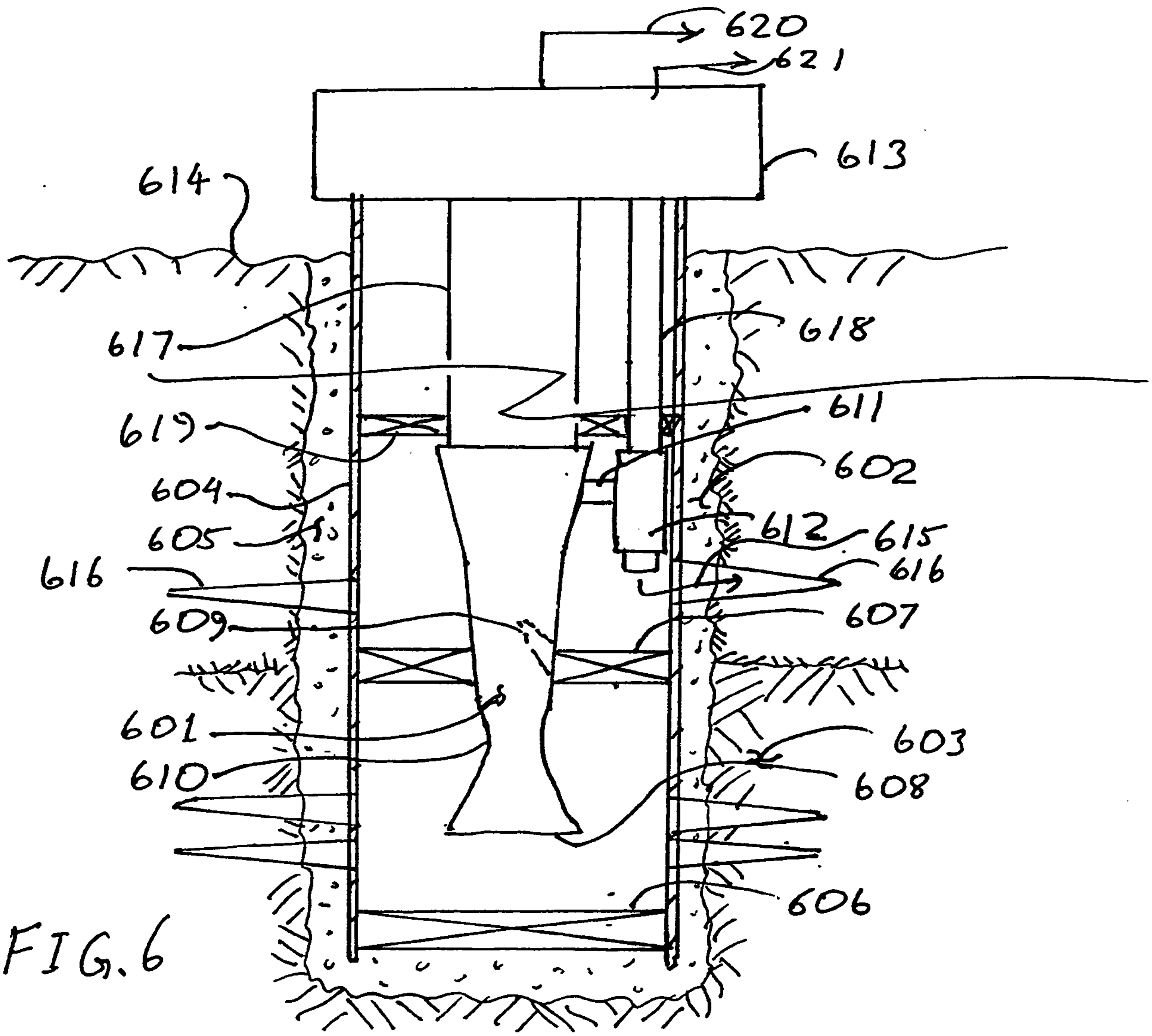

Maximum conduit radius (m)
0.3
0.25
0.2
0.15
0.1
0.05
0
0.0E+00
2.0E-07
4.0E-07
6.0E-07
8.0E-07
1.0E-06
1.2E-06
1.4E-06
Particle diameter (m)

FIG. 5

TH-1456



620
621
613
614
617
618
619
611
604
602
605
612
615
616
616
609
607
601
603
610
608
606


FIG. 6

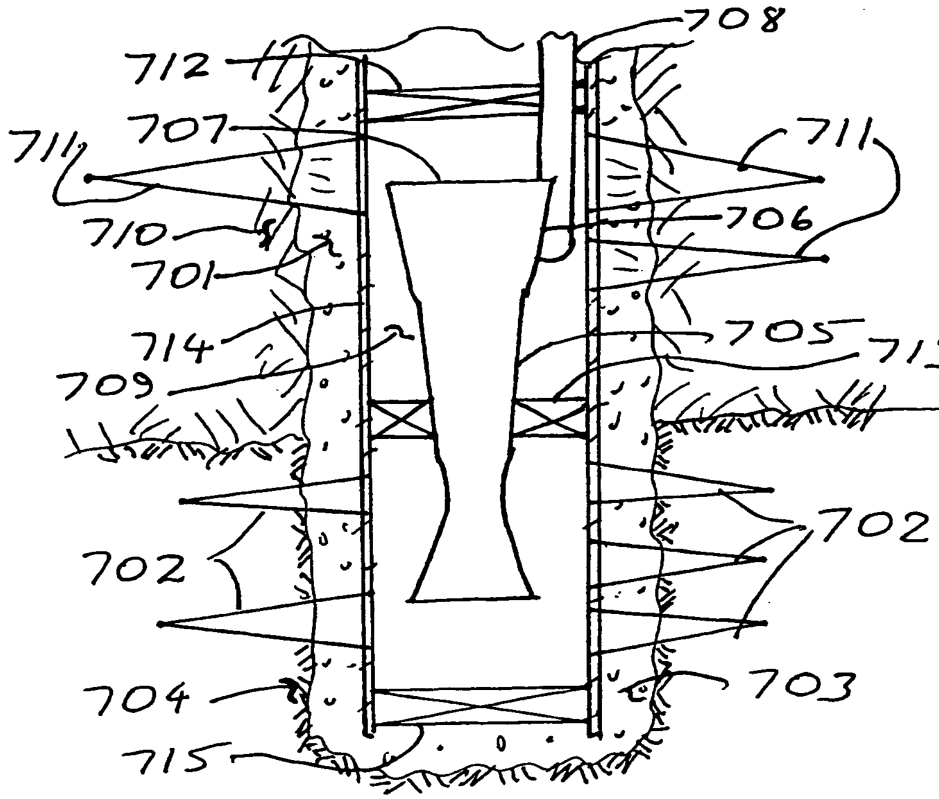

708
712
707
711
711
710
706
701
714
705
713
709
702
702
704
703
715

FIG. 7

THIS PAGE BLANK (USPTO)